Close out and Final report for
NASA Glenn Cooperative Agreement NCC3-814

Development of an Experiment High Performance Nozzle Research Program

Objectives and Task

As proposed in the above OAI/NASA Glenn Research Center (GRC) Co-Operative Agreement the objective of the work was to provide consultation and assistance to the NASA GRC GTX Rocket Based Combined Cycle (RBCC) Program Team in planning and developing requirements, scale model concepts, and plans for an experimental nozzle research program. The GTX was one of the launch vehicle concepts being studied as a possible future replacement for the aging NASA Space Shuttle, and was one RBCC element in the ongoing NASA "Access to Space" R&D Program (Reference 1). The ultimate program objective was the development of an appropriate experimental research program to evaluate and validate proposed nozzle concepts, and thereby result in the optimization of a high performance nozzle for the GTX launch vehicle. Included in this task were the identification of appropriate existing test facilities, development of requirements for new non-existent test rigs and fixtures, develop scale nozzle model concepts, and propose corresponding test plans. Also included were the evaluation of originally proposed and alternate nozzle designs (in-house and contractor), evaluation of Computational Fluid Dynamics (CFD) study results, and make recommendations for geometric changes to result in improved nozzle thrust coefficient performance (Cfg).

Accomplishments

Since May 01, 2000, under 3 successive grant elements, work has been performed by a Senior Research Associate (SRA) at OAI, Mr. Bernard J. Blaha, in assisting the NASA Glenn GTX Program generate technology and development plans for the experimental validation of high performance GTX RBCC nozzle concepts. Mr. Blaha was selected for this task based upon his extensive 37-year career at the NASA Glenn Research Center conducting and managing experimental research to improve high-speed aircraft nozzle performance. His research career covered a wide range of high-speed nozzle applications including Civil and Military, as well as past experience in rocket nozzle research for launch vehicles.

Besides helping to evaluate several initial NASA and contractor nozzle designs Mr. Blaha assisted the GTX Nozzle Team in identifying existing test facilities and new model test requirements needed to experimentally evaluate these designs and evolve an appropriate experimental test program necessary for the success of the GTX overall program. Specific work activities focused on evaluating nozzle program plans and progress, including Computational Fluid Dynamics (CFD) studies, and proposing new ones. He performed his own independent analyses of the initially proposed nozzle concept and combined with the initial CFD results identified significant areas of thrust performance loss in this original geometry. Results from these studies led to several design changes in the initially conceived propulsion system that included modifications in thruster type, nozzle ramp geometry, and cowl exit angle. His proposed design changes, along with inputs from others, were assessed in additional CFD initiatives and then incorporated in the evolving nozzle geometry design (Reference 2). Mr. Blaha also assisted in the evaluation of several other more unconventional improved-performance nozzle concepts developed by John Hopkins University (JHU) for the GTX using a unique Streamline Tracing Technique (STT).

The most significant accomplishment made by Mr. Blaha in the initial grant phase in NASA FY00 (5/01/00–9/29/00) was the development and documentation of aerodynamic requirements for a new nozzle test rig and several scale (nominally 7.0%) nozzle model concepts. This new test rig, shown in Figure 1, was proposed for testing a series of GTX scale nozzle models in-house at NASA Glenn in the 8×6 TWT and 10×10 SWT wind tunnels with external flow. Initially it was felt by the program managers that it would be more beneficial to the overall test program to develop an internal NASA test capability. The major NASA GTX Program was being planned to start with extensive small-scale model testing of all the vehicle critical components, but eventually evolve into to a large-scale flight demonstration program. It was identified by Mr. Blaha that, appropriate high-pressure air systems still exist at NASA Glenn (Reference 3), and these systems had been used extensively in the past for rocket nozzle tests in the wind tunnels early in the NASA Space Programs (e.g., Atlas-Centaur, Saturn, and Apollo). However, all the test rigs that had been used for rocket nozzle testing early in the space program in the 8×6-ft. and 10×10-ft. wind tunnels had long since been destroyed. Consequently to meet the original GTX program objectives a new nozzle test rig would be required that would use the existing high-pressure air systems. As a result Mr. Blaha then proceeded to develop a new nozzle test rig design for use in the wind tunnels. A corresponding aerodynamic-design 'Requirements-Document' was drafted by him and a final copy of this document was submitted to the GTX Program Office in August 2000. This document provided detailed test rig and scale nozzle model aerodynamic design and test instrumentation requirements that would allow the NASA Glenn Engineering Design and Analysis (ED&A) Division to develop a detailed mechanical design and initiate fabrication. This new test capability does not currently exist in the country but would eventually be critical to the success of this major (at the time) NASA Program. As proposed by Mr. Blaha this rig would be similar in design to a highly successful nozzle test rig used at NASA Lewis throughout the 1960's and 1970's in the 8×6 SWT for the original Supersonic Transport (SST) Program (shown in Reference 4). With two separate, independently controlled, high-pressure internal air-flow supplies it would uniquely allow the testing of various GTX nozzle concepts with a combined simulated thruster rocket flow and separate ram/scram jet flows in the NASA Glenn 8×6-ft. Transonic and 10×10-ft. Supersonic Wind Tunnels. The unique force-balance in this rig would result in the measurement of the thrust-minus-drag performance for varying GTX nozzle concepts, over the critical transonic speeds of the proposed multi-propulsion mode launch vehicle trajectory. Also included in this document were suggested ideas for model nozzle component attachments for easily varying future designs and components such as modifications to ramp and cowl geometries. He also provided designs and recommendations for other required test hardware including calibration fixtures and ASME reference nozzles.

During this same period Mr. Blaha investigated two additional possible test facilities for static (no external flow) nozzle testing at Glenn. These included the CE-22 nozzle test stand and the Propulsion Systems Laboratory (PSL), but neither of them were pursued by the GTX Program Office. The CE-22 facility is a smaller nozzle test facility located in the Engine Research

GTX WIND TUNNEL NOZZLE TEST RIG

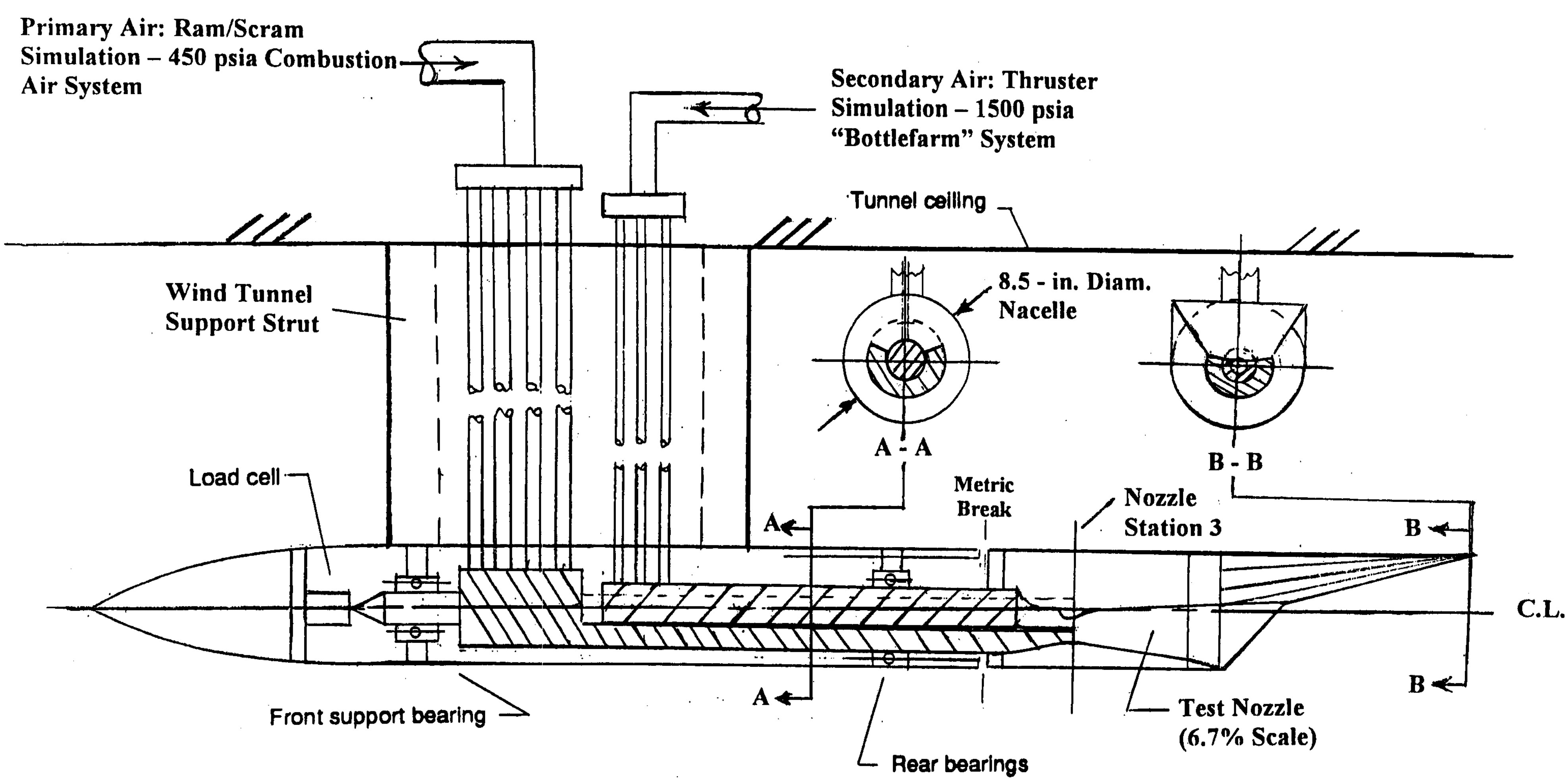


Figure 1. - Proposed jet-exit-rig concept for testing GTX RBCC scale nozzle models in the NASA Glenn 8x6-Ft. TWT and 10x10-Ft. SWT wind tunnels.

Building (ERB) at NASA Glenn, but has been very useful in past and recent nozzle research programs. The PSL facility has two large test tanks for testing full-scale aircraft engines, and is again located at NASA Glenn. Each test tank has air supply and force measurement capabilities, but would require some modifications for GTX testing and would be very expensive to use. Both of these test facilities are heavily used by the nation's aero propulsion industry for the development of advanced new Commercial and Military aircraft engine and nozzle systems. Relative to the GTX vehicle requirements, however, both facilities have limited maximum air flow supply pressure capability, and would provide therefore a much more restricted range of nozzle test conditions.

Since the GTX Program funding began to be significantly reduced in NASA FY01 it became apparent that the development of a new test rig would not be affordable. Other more economical approaches for scale nozzle testing had to be pursued. The most significant activity completed by Mr. Blaha during the second grant phase conducted in FY01 (9/30/00–8/31/01) therefore included the identification of two existing, and unique in the country, contractor test cells. These test cells are already equipped with the appropriate high pressure and air flow supply capabilities needed for testing scale GTX nozzle models across the four propulsion modes of operation planned for the GTX vehicle from sea-level take-off to orbit insertion. The two contractor test facilities are the Aero Systems Engineering ASE/FluiDyne Company Channel 8 and Channel 9 static high-speed and pressure, aero and launch vehicle, nozzle test cells located in Minneapolis, MN (described in References 5 and 6 respectively). The Channel 8 cell has the appropriate multiple high-pressure air-flow capabilities required for the combined rocket and ram/scram propulsion simulations needed for the GTX Propulsion Modes 1 to 3 conditions. The Channel 9 cell has only a single flow capability, but this system has a heated air supply. Higher temperature air is needed to prevent "air liqui-faction" errors that would result from using ambient temperature air at the very high nozzle pressure ratios (NPR's) of the GTX vehicle in the Mode 4 operation conditions seen at the very high altitude simulations of orbit insertion. With the very high nozzle exit area expansion ratio of the GTX nozzle, and the corresponding NPR's at very high altitude conditions, the static temperature of the jet exhaust can be significantly lower than where the Nitrogen component of the nozzle supply air would begin to liquefy. Without a heated air supply, these conditions have been found in past tests to significantly impact the measured thrust performance of the test nozzle.

Mr. Blaha then proceeded to generate the conceptual aerodynamic design for a single 5.0 percent-scale GTX nozzle model appropriate for testing in both of these cells. He then drafted a second "Requirements Document" that defined the aerodynamic design details, instrumentation, and test plans for this scale model to be mechanically designed and fabricated, again in-house, by the NASA Glenn ED&A Division. As identified by Mr. Blaha these two unique test cells are well known, extensively calibrated, and are also heavily used by the Aero Propulsion Industry in the country to develop most of the current aircraft nozzles used today (both Civil and Military). More recently they further had been used to test hypersonic vehicle nozzle concepts proposed for the major NASA National Aerospace Plane Program (NASP) and other unique very high-speed Military programs. Even though test costs were projected to be high, since these test cells already existed and were fully calibrated, they could still more economically and rapidly provide static internal nozzle performance for the GTX program across the complete range of the proposed vehicle propulsion conditions from sea level take-off conditions to orbit insertion. This was particularly true since only a single model would be needed. A final copy of the document was submitted to the GTX Program Office in June 2001 and a detailed mechanical design effort was soon initiated at Glenn at the end of FY01.

Under a third grant element executed in NASA FY02 (9/01/01–8/31/02) Mr. Blaha continued to support and provide technical input to the ED&A Division throughout the model mechanical design process. This process was completed in FY02 and plans were developed for the initiation of model fabrication and testing in the Contractor Facilities beginning late in FY–03, contingent on program funding. A three-view schematic drawing of the nominally 5.0 percent scale model is shown in Figure 2. Throughout this grant element Mr. Blaha interacted with NASA Glenn and the proposed contractor to determine testing feasibility requirements and develop estimated test costs. Detailed drawings of the model installed in the contractor test facilities were developed by ASE/FluiDyne and are shown in Figure 3. The tables on the figure show the range of test requirements and the corresponding facility capabilities to meet those conditions. Because of Mr. Blaha's input, as stated above, it would now be feasible, and significantly more economical to the program, to fabricate a single model that could be tested in the two 'Contractor' facilities across the four required propulsion modes of the GTX launch vehicle. Unfortunately funding for the overall GTX Program was terminated before model fabrication could be initiated.

Through a series of "No-Cost" extensions to the third Grant element Mr. Blaha continued to support a few remaining elements of the original GTX program which were allowed to continue in NASA FY03 to completion. He continued to review results from the previously mentioned JHU grant including their recent streamline tracing nozzle concept developments and analyses, and also results from another small-scale nozzle test conducted at the University. Likewise he continued to review results from the ongoing series of CFD studies that started at NASA Marshall and were eventually transferred to NASA Glenn. Mr. Blaha further supported the remaining GTX program elements by providing input in responding to a New NASA Initiative for the Next Generation Launch Technology Program (NGLTP) Office. Elements from Mr. Blaha's proposed GTX work were submitted as part of a Government Led Solicitation Proposal in response to this program's NRA Announcement in April 2003. If accepted by the new NGLTP Program the proposed GTX 5.0 percent scale nozzle model would be fabricated and tested to develop a database that would be used to more rapidly validate the CFD codes used to develop the early GTX design concepts. Validated CFD codes will be critical tools needed for the timely success of this, and any other, new launch vehicle initiative. Leveraging the already completed work from the terminated GTX Research Program, could possibly be an economical and expedient element in the new NGLTP initiative.

Summary

As stated above, and defined in the original grant proposal, Mr. Blaha has addressed and completed all of the specified requirements. He has provided input for the identification and assessment of the capabilities of existing NASA and Industry high-speed nozzle test facilities, and developed the aerodynamic design of a new nozzle test rig that would be needed for testing in the NASA Glenn high-speed wind tunnels. He developed and provided aerodynamic design details and test plans for a single scale nozzle model for testing in two contractor nozzle test

5 % - SCALE GTX NOZZLE MODEL

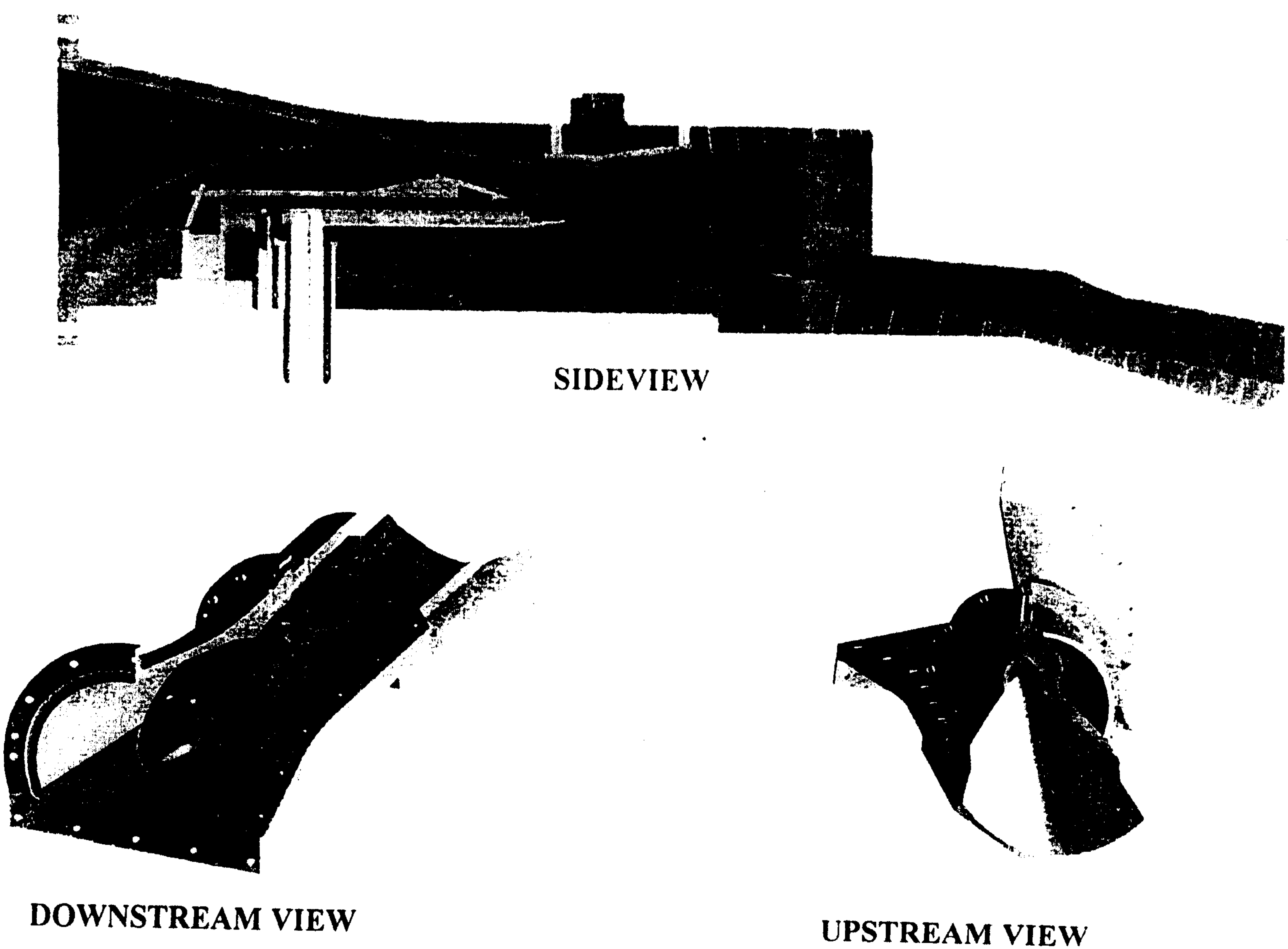
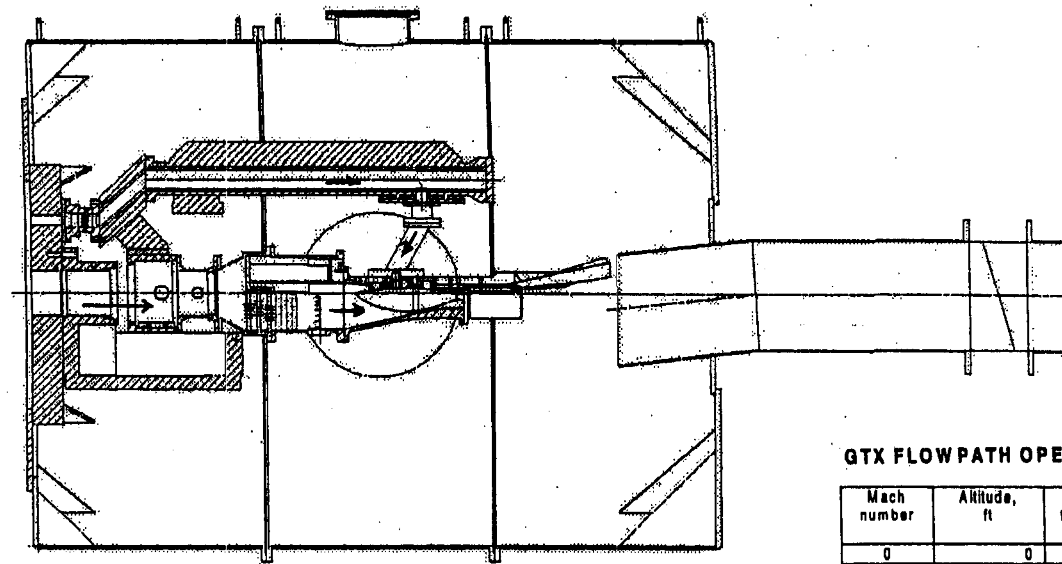


Figure 2. - Three-view drawing of 5.0% scale GTX nozzle model for testing in the ASE/FluiDyne Channel 8 and Channel 9 Static Test Facilities.

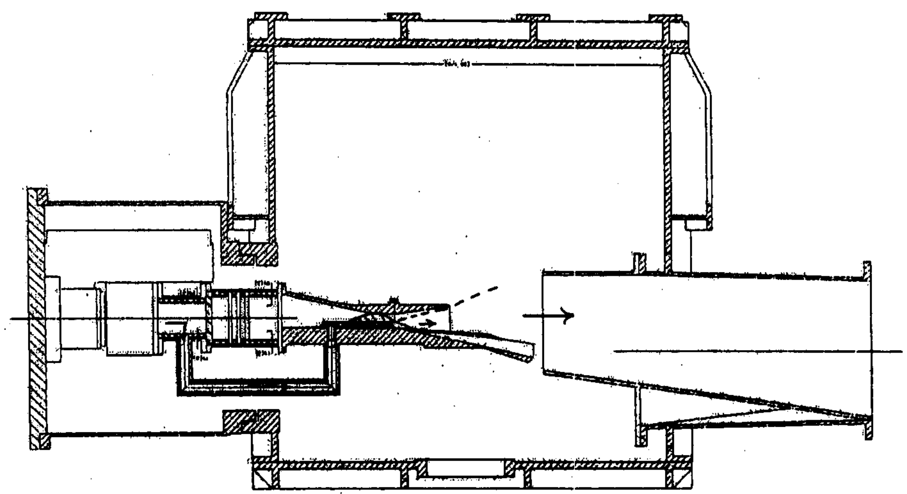
5% - SCALE GTX NOZZLE MODEL IN AERO SYSTEMS ENGINEERING (ASE/FluiDyne) STATIC TEST FACILITIES



CHANNEL 8 – PROPULSION MODES 1 to 3.

GTX FLOWPATH OPERATING ENVELOPE.

Mach number	Altitude, ft	Combustor total pressure, psia	Nozzle pressure ratio
0	0		
2	27,280	24.3	4.9
2.5	36,952	33.0	10.5
3	44,625	44.0	20.1
4	56,682	80.6	65.9
5	66,055	131.2	167.1
6	79,928	102.3	251.0
8	92,349	165.0	718.0
10	102,000	289.5	1961.7
12	110,000	488.5	4741.5
ATO	150,000+		Inf



SCALE MODEL TEST CONDITIONS

Propulsion Mode	Mach Range	NPR Range		
		Thruster	Ram (A*3)	Scram (A*2)
1	SLS < Mo < 0.5 0.5 < Mo < 2.5	100 ---> 300 300 --->100	off 5 ---> 10.5	off off
2	2.5 < Mo < 5.5	off	10.5 ---> 170	off
3	5.5 < Mo < 10.0	off	off	170 ---> 5000
4	10 < Mo < ATO	5000 ---> 90000 +	off	off

CHANNEL 9 – PROPULSION MODE 4.

Figure 3. - Schematic drawings of 5.0% scale GTX nozzle model installed in the ASE/FluiDyne Static Test Facilities.

facilities. He also provided assessment for several other proposed nozzle concepts, and performed a preliminary review of several models proposed for testing in University facilities. Based upon his extensive test experience he was able to further provide unique scale model nozzle component-attachment details for easily varying alternate nozzle component geometries such as ramps and cowls, and made recommendations for the additional test hardware needed for a new test rig that included unique instrumentation and conceptual designs for required calibration fixtures. However, due to funding limitations and unexpected cuts, the experimental plans and model tests proposed by Mr. Blaha were delayed in the GTX Program, that was eventually terminated by NASA.

Additional Program Contributions and Awards

During the conduct of these grant elements Mr. Blaha continued to support the GTX Program by participating in weekly GTX Team meetings, meetings with NASA Program Managers, contractors, and University representatives. He also co-authored two papers presented (by NASA personnel) at successive Joint Army, Navy, NASA, and Air Force (JANNAF) Conferences. The first (Reference 7) was presented in November 2000 in Monterey CA, and the second (Reference 8) in April 2002 in Destin FLA. Lastly, on June 30, 2002 Mr. Blaha participated, with his GTX Teammates, in a special NASA Group Achievement Award (GAA). This award cited the GTX Team for "the significant progress that you made toward demonstrating the feasibility of rocket-based combined cycle (RBCC) propulsion for reusable launch vehicles, despite adverse conditions". As further cited in the Award Justification it was recognized that "with minimal funding, the team redesigned the flow-path geometry and successfully demonstrated its design performance Experimentally." Through his efforts Mr. Blaha, and ultimately OAI, had made numerous inputs and significant contributions to this team award.

References

1. Trefny, C.J., "An Air-Breathing Launch Vehicle Concept for Single-Stage-to-Orbit," AIAA Paper 99-2730, July 1999.

2. Trefny, C.J., and Roche, J.M., "Performance Validation Approach for the GTX Air-Breathing Launch Vehicle," Proceedings of the JANNAF 26th Air-Breathing Propulsion Subcommittee Meeting, Destin, FLA, April 2002.

3. Soeder, R.H., "NASA Lewis 8×6-Foot Supersonic Wind Tunnel User Manual," NASA TM 105771, February 1993.

4. Stitt, L.E., "Exhaust Nozzles for Propulsion Systems With Emphasis on Supersonic Cruise Aircraft," NASA Reference Publication, RP-1235, May 1990.

5. Flugstad, T.H., Romine, B.M., and Whittaker, R.W., "High Mach Exhaust System Concept Scale Model Test Results," AIAA/SAE/ASME/ASEE 26th Joint Propulsion Conference, AIAA Paper 90-1905, Orlando, FLA, July 1990.

6. Idzorek, J.J., "Development of a High Area Ratio Nozzle Thrust Stand," AIAA/ASME/SAE/ASEE 24th Joint Propulsion Conference, AIAA Paper 88-2964, Boston, MA, July 1988.

7. Smith, T.D., Canabal III, F., Rice, T., and Blaha, B., "Development of an Integrated Nozzle for a Symmetric RBCC Launch Vehicle Configuration," Proceedings of the JANNAF 25th Airbreathing Propulsion Subcommittee, APS-CS-1F1, Monterey, CA, November 2000.

8. Smith, T.D., Blaha, B., Rice, T., and Yungster, S., "Integrated Nozzle Design for the GTX RBCC Flowpath", Proceedings of the JANNAF 26th Airbreathing Propulsion Subcommittee Meeting, APS-4D1, Destin, FLA, April 2002.